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Although winter typhoons can be as intense and destructive as seasonable ones, little research has been devoted to these "off-season tropical cyclones." This synoptic and dynamic study is of such a storm, Typhoon Nancy (19-27 Feb 70). It examines anomalies in the February 1970 circulation patterns over the Western Pacific and

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20. Abstract (continued)

utilizes them to explain the formation and development of Nancy. Special emphasis is placed on the impact of cross-equatorial interactions during the storm's genesis. The study indicates that the rarity of "off-season tropical cyclones" may result, in part, from the absence of two conditions north of the equator during winter: low-level westerly winds and a sea surface temperature maximum. Evidence is also presented to suggest that the wall cloud and subsequent eye formation is contingent upon a rapid increase of upper level divergence above the developing system.

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CROSS-EQUATORIAL INTERACTIONS IN THE DEVELOPMENT OF A WINTER TYPHOON: NANCY 1970

by

CHARLES P. GUARD
CAPTAIN, USAF

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NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY
MONTEREY, CALIFORNIA 93940

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CONTENTS

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1. INTRODUCTION

One area of meteorological research which has been neglected is that involving typhoons that occur during winter. Although rare, these "off-season tropical cyclones"[1] can be as intense and devastating as those which occur during the normal typhoon season.

These unseasonable tropical systems are most common in the western North Pacific, but Gibbs (1956) also refers to the occurrence of similar storms in the Australian regions (May-November). According to Joint Typhoon Warning Center, Guam statistics (1946-1975), the number of typhoons from December through April is approximately one-seventh the number during the remaining months.

Several authors {Riehl (1954), Palmén (1956), Wilkie (1964), and Palmén and Newton (1969)} have listed a number of conditions necessary for the formation of tropical cyclones. The conditions are: (1) large sea areas with a sea surface temperature above 26°C; (2) weak vertical shear in the basic wind field; (3) a minimum value of the Coriolis parameter; (4) a pre-existing, low-level disturbance; and (5) upper tropospheric outflow above the region of development. Gray (1975) also demonstrates the need for high relative humidity in the middle troposphere, a gradient of Θ_e between the surface and middle troposphere and cyclonic relative vorticity at the planetary boundary layer.

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[1] "Off-season tropical cyclones" are those in the western North Pacific which occur from December through April.

It seems plausible to assume that the structure and mechanics of tropical cyclones are similar, regardless of season. An exception to this hypothesis results from larger thermal and pressure gradients in the northern semicircle during winter which produce greater intensity for any given minimum sea level pressure, especially in weaker systems.

Primary differences between winter and the other seasons arise from changes in the general circulation, which in turn alter the thermal and dynamical characteristics of the atmosphere and the mixed layer of the underlying ocean. At lower levels in the tropics of the western Pacific from May through November, southwesterly winds cross the equator and merge with northeasterly trades to form the Northern Hemisphere near equatorial trough (NET). This trough is the spawning grounds for most tropical cyclones. North of the equator, from December through April, the low-level flow is generally northeasterly. Upon crossing the equator, the winds turn counterclockwise producing the northwest monsoon of Australia and Indonesia, thus eliminating the Northern Hemisphere NET and with it the tropical cyclone spawning grounds. Since the tropical upper tropospheric trough (TUTT), which can also induce tropical cyclone development (Sadler, 1974), is non-existent in winter, the NET must be reestablished before tropical cyclogenesis can occur in the winter season.

February 1970 was anomalous both in its circulation and in its distribution of weather, at least in the tropical and subtropical regions between 90°E and the Dateline. An understanding of the circulation in these regions prior to the formative stages of Typhoon Nancy (February 19-27, 1970) is essential for an interpretation of the cross-equatorial interactions that influenced her formation and development. Accordingly, this investigation comprises two parts:

(1) Background (Section 2), which is descriptive of 8-15 February 1970, examines the salient circulation anomalies and utilizes them to explain the resulting circulation and weather distribution in the tropics of both hemispheres; and (2) The Development of Typhoon Nancy (Section 3) which covers the period (16-20 February) leading up to the formation of a tropical depression and its subsequent development into Typhoon Nancy. A locator map of the geographical areas discussed in this paper is presented as Figure 1.

2. BACKGROUND

On 8 February 1970, the Southern Hemisphere NET in the South Indian Ocean became very active, producing four tropical cyclones during a three-day period. On 9 February, the NET east of Australia also became active and generated three tropical cyclones over a two-day period. Six of these systems can be seen in the 15 February ESSA 9 satellite composite (Figure 3). The reasons for the prolific cyclogenesis are undoubtedly complex, but it is apparent that certain anomalies in the circulation patterns created a highly favorable environment for cyclogenesis.

Wind observations at the 200-mb level at the Australian stations of Giles, Alice Springs and Cloncurry and at Noumea, New Caledonia, are shown in Table 1.

Table 1. February 1970 mean 200-mb winds and the February long term mean 200-mb winds at selected stations.

PLACE	FEBRUARY 1970	FEBRUARY MEAN
Giles, Aus. (25°02'S/128°18'E)	244° 16kt	257° 32kt
Alice Springs, Aus. (23°48'S/136°53'E)	230° 22kt	261° 26kt
Cloncurry, Aus. (20°40'S/140°30'E)	260° 22kt	273° 16kt
Noumea, New C. (22°16'S/166°27'E)	275° 47 kt	291° 32kt

The February 1970 mean winds all possess a more southerly component than their long term mean. Analyses indicate both greater than normal equatorward penetration of the upper tropospheric mid-latitude trough and a shift in the long wave pattern. Table 1 shows that winds at Noumea were 15 kt

stronger than the long term mean. During the ten days prior to the onset of cyclogenesis east of Australia, 200-mb winds at Noumea were in excess of 65 kt and exceeded 80 kt during half of this period. On the 9th, winds at Cloncurry and Alice Springs were 25 kt and 10 kt respectively while those at Noumea were 85 kt. This regime imposed strong upper tropospheric divergence just poleward of the region of development. The "low-index" situation over eastern Australia would suggest a "low-index" regime in the hemispheric wave pattern and, consequently, over the Indian Ocean.

On the 11th, upper level, southeasterly winds increased over the region between the Philippines and the eastern Carolines. A day later, low-level northwesterly winds accelerated over New Guinea (see Tables 2 and 3). Upper level winds again accelerated on the 16th and low-level northwesterly winds north of New Guinea increased on the 17th. The low-level accelerations were confined to a much narrower band than those at the upper level. It appears likely that the low-level accelerations were in some way a response to the upper level accelerations. An examination of January and February upper tropospheric winds from 1965 to 1972 indicates that large accelerations occur between one and two times each month over the Caroline Islands and about three times a month over the Palau Islands. They are greatest between Koror and Ponape, the area where most off-season tropical cyclones develop (Gray, 1970). During the accelerations, maximum winds are observed between the 175- and 125-mb levels. They are accompanied by intense convection over the Carolines, but this is not usually observed over the Palau Islands.

Table 2. Gradient level winds from 10-17 February 1970 and the February long term mean gradient level winds (LTM) for selected stations. Data is from 00Z observations. Dashed lines indicate data missing or not available.

Date	Port Moresby (09°26'S/147°13'E)	Lae (06°44'S/147°00E)	Manus Island (02°04'S/147°26'E)	Songkhla (07°11'S/100°37'E)
10	330° 35kt	---------	320° 30kt	090° 28kt
11	320° 25kt	300° 25kt	320° 25kt	075° 34kt
12	300° 50kt	280° 50kt	300° 20kt	065° 26kt
13	320° 35kt	290° 50kt	020° 15kt	140° 10kt
14	310° 15kt	310° 20kt	330° 20kt	120° 18kt
15	310° 20kt	---------	---------	085° 20kt
16	290° 10kt	300° 25kt	310° 40kt	070° 36kt
17	330° 20kt	270° 15kt	300° 50kt	075° 36kt
LTM	310° 12kt	---------	---------	084° 14kt

Table 3. 200 mb winds from 10-17 February 1970 and the February long term mean 200 mb winds (LTM) for selected stations. Data is from 00Z observations.

Date	Koror (07°20'N/134°29'E)	Truk (07°28'N/151°51'E)	Ponape (06°58'N/158°13'E)
10	130° 34kt	133° 26kt	145° 42kt
11	139° 50kt	117° 44kt	132° 56kt
12	146° 40kt	118° 44kt	126° 46kt
13	145° 22kt	120° 44kt	128° 42kt
14	122° 22kt	124° 46kt	142° 40kt
15	095° 24kt	126° 30kt	125° 20kt
16	130° 26kt	122° 48kt	144° 58kt
17	134° 42kt	141° 32kt	130° 30kt
LTM	119° 24kt	122° 16kt	117° 17kt

Prior to the prolific cyclogenesis east of Australia, cloudiness over Indonesia was profuse. ESSA 9 satellite composites indicated intense convective activity, which is characteristic of the northwest monsoon. The counterclockwise curving cross-equatorial drift,[2] supplying low-level convergence, coupled with divergent upper tropospheric flow, is responsible (Ramage, 1971). The upward branch of the Hadley cell transports the released heat energy northward where it contributes to the maintenance of the subtropical jet (Palmen and Newton, 1969).

From the 13th through the 16th of February, the vigorous convection over Indonesia subsided and did not recur until the end of February (after recurvature of Typhoon Nancy). It is interesting to examine the conditions contributing to the suppression of convection over Indonesia. First, the normally divergent, upper level regime over Indonesia was replaced by a convergent one. Secondly, widespread subsidence from the tropical cyclones to the south subdued vertical development. Finally, by the 17th, the normally strong, low-level convergence over Indonesia was reduced by the establishment of the NET north of the equator.

The normal 140-kt jet stream east of Japan exceeded 200 kt from the 15th through the 18th. Upper tropospheric analyses over the Indian Ocean regions indicate that much of the outflow from the tropical cyclones west of Australia was directed northward over southern Asia and into the region of the subtropical jet. It would not seem unreasonable to assume that heat of condensation, pumped northward from the tropical cyclones, played a significant role in strengthening the East Asian subtropical jet.

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[2]Johnson and Mörth (1960) labeled cross-equatorial flow from high to low pressure as "cross-equatorial drift."

At the height of the Southern Hemisphere tropical cyclone activity, skies over Australia became relatively cloudless. Storms, both east and west of the continent, provided unusually strong subsidence which suppressed convection. At the surface, pressures fell as the heat low intensified. In the middle troposphere, heating due to adiabatic compression by the subsiding air produced anticyclogenesis throughout the middle and upper troposphere which persisted throughout the remainder of February.

3. THE DEVELOPMENT OF TYPHOON NANCY

Between 00Z on the 15th and 00Z on the 16th, the upper tropospheric winds at Funafuti (08°31'S, 179°12'E) and Pago Pago (14°20'S, 170°43'W) weakened, while those above the Marshall and Caroline Islands exhibited large increases; consequently, strong, divergent upper tropospheric flow resulted between Funafuti and the Caroline Islands. During this period, the 250-mb winds at Ponape changed from 138° at 10 kt to 145° at 54 kt.

ESSA 9 satellite pictures (Figures 3 and 4) indicate that convection over the Caroline Islands, increased from the 15th to the 16th. Redistribution of heat of condensation was probably responsible for some of the strong accelerations but the abruptness and magnitude of the changes suggest an additional impetus. Perhaps the impetus was from the Northern Hemisphere where the jet stream exceeded 200 kt; or, perhaps it was from the Southern Hemisphere where the TUTT was very intense. Winds at the 250-mb level at Penrhyn Island (09°01'S, 158°04'W) were 170° at 55 kt and at Raratonga Island (21°12'S, 159°46'W) were 170° at 50 kt. For the respective stations, the mean 250-mb winds for February are 200° at 15 kt and 260° at 10 kt. It seems likely that energy interactions between the strong circulations in both hemispheres were responsible for the accelerations. The 250-mb level above the tropics of the Northern Hemisphere was dominated by a massive anticyclone which extended from Southeast Asia to 170°W (see Figure 2).

The surface analysis on the 16th (Figure 5) shows an anticyclone over central China which produced a moderate surge over Southeast Asia and the South China Sea. Winds in the South China Sea accelerated some 20 kt from the 15th to the 16th, while gradient level winds at Songkhla increased from 20 kt to 36 kt. These accelerations occurred simultaneously

with those in the upper levels above the Caroline Islands (see Tables 2 and 3), a manifestation of accelerations in the upper and lower branches of the Hadley cell.

The normal cross-equatorial drift which recurves near the equator, was displaced northward producing a surface trough north of the equator and westerly winds along the equator. Gradient level winds at Manus Island (Momote, 02°03'S 147°25'E) were 40 kt while the northeast trades were 20 to 30 kt over the Carolines. Consequently, a region of strong cyclonic wind shear developed south of the Caroline Islands. Sadler (1967) shows that tropical vortices develop only in regions where two opposing wind fields produce cyclonic shear and the accompanying positive vorticity. The strong divergent upper level winds, coupled with strong convergent low-level winds combined to produce widespread convection (Figure 4).

On the 16th, the 00Z vertical profile of Ponape exhibited large 24-hour height falls throughout the tropospheric column. Smaller 24-hour height falls occurred at Truk, but lagged those at Ponape by about 12 hours (Figures 6 and 7). It seems plausible to assume that the region of lowest surface pressure between Truk and Ponape would exist within the NET beneath the region of greatest height falls.

The time cross sections of Truk and Ponape (Figures 6 and 7 respectively) indicate that high middle tropospheric relative humidities occurred at Ponape prior to their occurrence at Truk. Convective rains at Ponape preceded those at Truk by 15 hours. By 12Z on the 16th, the 75 percent isohume was above the 400-mb level at Ponape and above the 300-mb level at Truk. Gray (1975) states that, over tropical oceans, high concentrations of middle level water vapor tend to enhance, rather than inhibit, deep cumulus convection. This middle level high humidity dilutes the effects of entrainment and reduces evaporation of condensed water between the mid-levels and the surface. This allows for greater enthalpy production which is conducive to vortex development.

Bhumralkar (1974) showed that a moist column of air would create a surface pressure more than 2 millibars lower than a similar column of dry air. Thus, hydrostatically, the moisture influx into the region would contribute to an overall reduction of surface pressure, increasing the surface pressure gradient and further intensifying the surface trough. Since tropical disturbances exhibit small surface pressure gradients, the hydrostatic contribution of water vapor could play a significant role in early vortex development.

By 00Z on the 17th, the surface and gradient level flow in the tropics had undergone considerable change as the normal cross-equatorial drift into Indonesia was interrupted by the formation of a NET north of the equator. Low level flow north of the NET had increased to 40 kt at Truk, while to the south, Manus Island exhibited northwesterly winds of 50 kt and a ship reported 20 kt westerly winds at 3N-152E.

It is interesting to examine the reasons for the formation and persistence of a NET in the Northern Hemisphere during February 1970. It appears that the distribution of the sea-surface temperature (SST) may have played an important role in the anchoring and maintenance of the Northern Hemisphere NET. An analysis of the February 1970 SST (Figure 10) shows that the SST was from 1° to 2°C warmer than normal in the Northern Hemisphere tropical regions. The sea-surface isotherms indicate a maximum from 4N south of Ponape, westward to 4N, 138E, northward to 10N, 135E and southwestward to the southern Philippines. Ramage (1974) has shown that near-equatorial troughs are thermally anchored. He presents evidence that weak surface troughs in the pressure field are associated with SST maxima. It seems plausible to assume that the region of maximum SST would anchor the NET once the wind trough and pressure trough became superimposed.

It is well observed that sustained deep convection requires sufficient thermal buoyancy. Gray (1975) demonstrates that potential moist buoyancy ($\frac{\partial \Theta_e}{\partial p}$) between the surface and middle troposphere is primarily influenced by SST. Therefore, the above-normal SST (1° to 2°C) observed during February 1970 would contribute to deeper and more sustained convection than normally observed over the region.

During the 18th, 6.17 inches of rain was recorded at Truk. A portion of the depression's broad center crossed the island between 18Z on the 18th and 00Z on the 19th, exhibiting a minimum surface pressure of 1004.7 mb (Figure 6). From the surface to 405 mb, temperatures were as much as 2°C warmer at 12Z on the 18th than at 12Z on the 17th. This reflects an accumulation of enthalpy similar to that observed by Lopez (1968). Since data was not available above 405 mb on the 18th, upper tropospheric heating could not be determined. Lopez (1968) suggests that both divergence and ventilation (horizontal advection of heat) are important in preventing accumulation of enthalpy. However, Gray (1975) indicates that values of divergence are similar above both developing and non-developing disturbances. He proposes that ventilation is the primary inhibitor of enthalpy accumulation. This seems likely since meteorological satellite data indicate divergence (at some level) above nearly all disturbances, whether they develop or not. Figures 4, 9, 16, and 17 indicate the existence of upper level divergence prior to development of Nancy.

Figure 6 illustrates a considerable decrease in middle level moisture as the tropical depression approached and crossed Truk. This is contrary to what would be expected during this stage of development. Towering cumulus and moderate to heavy precipitation were observed throughout the period; consequently, the drying cannot be attributed to subsidence.

Between the 18th and the 19th, the upper level circulation changed radically over the Caroline Islands (Figures 12 and 13). Southwest winds over Ponape indicate the existence of an upper level cyclone between Truk and Ponape. Near the equator, 250-mb flow from the 18th to the 19th was east-southeasterly. Southern Hemisphere air crossing the equator under the constraint of conservation of absolute vorticity would have acquired anticyclonic, not cyclonic, relative vorticity. Analyses of the 700-, 500-, 400-, and 300-mb levels indicate a source of winds possessing a westerly component which would, upon crossing the equator, acquire cyclonic relative vorticity. Over Australia, the middle and upper troposphere was dominated by an anticyclone. On the 18th, air emanating from the anticyclone between the 700- and 400-mb levels, accelerated northeastward producing cross-equatorial flow toward the Caroline Islands. As the surge of southwesterly winds moved northward they deepened in vertical extent and, upon crossing the equator, acquired cyclonic relative vorticity (up through the 250-mb level at Ponape). Figure 11 illustrates the vertical wind profile between Australia and the Carolines at 00Z on the 19th. Figure 13 shows the resulting upper level cyclone between Truk and Ponape. Additional analyses of the middle and upper troposphere indicated that the cross-equatorial flow, at all levels, had subsided by 12Z on the 19th. The reestablishment of easterlies at the 250-mb level at Ponape is shown in Figure 19.

The upper tropospheric cyclone over the Carolines played a dual role in the development of Typhoon Nancy. First, cyclonic vorticity supplied by the cross-equatorial flow provided a vertical coupling of the low and middle levels of the storm with the upper levels. Secondly, it reduced ventilation within the middle troposphere and the lower part of the upper troposphere, allowing for a greater accumulation of heat.

For continuity purposes, the surface analyses and satellite photographs for the 18th and 19th are shown as Figures 14-15 and 16-17, respectively. Aircraft reconnaissance indicated that Nancy was approximately 100 nm northwest of Truk at 12Z on the 19th (Figure 18). Since Nancy was moving away from Truk, surface pressures at the island would be expected to rise but, from 18Z on the 18th to 18Z on the 19th, pressures fell from 1004.7 mb to 1003.4 mb. This reflects the deepening of Nancy.

A computer program utilizing data from the 250-mb streamline and isotach analyses enabled analysis of the divergence and vorticity fields at 250 mb. The vorticity analyses were used to qualitatively verify the validity of the divergence analyses. The divergence and vorticity patterns were found to be compatible.

At 00Z on the 16th the greatest divergence at 250 mb exceeded 2.6×10^{-5} sec^{-1} south-southwest of Ponape. By 00Z on the 17th maximum divergence above the Carolines had decreased to 1.7×10^{-5} sec^{-1} and had shifted westward midway between Truk and Ponape at 5N. This is consistent with the height falls observed in Figures 6 and 7. During the 18th and 19th, the 250-mb divergence weakened to values of $\pm 0.5 \times 10^{-5}$ sec^{-1}. This weakening reflects the existence of the upper level cyclone between Truk and Ponape.

From 12Z on the 19th to 00Z on the 20th, 250-mb divergence above the tropical system increased from -0.5×10^{-5} sec^{-1} to 2.0×10^{-5} sec^{-1}. Reconnaissance aircraft indicated that surface pressures in the center of the storm fell nearly 15 mb over this 12-hour period. Furthermore, wall cloud formation was observed at 23Z on the 19th. The coincidence of the rapid increase in divergence, large surface pressure falls, and the formation of a wall cloud suggests that eye formation may be contingent upon a large rate of change in the upper level divergence above the developing system. The rapid export of

mass could account for large surface pressure falls which occur so rapidly that low-level convergence cannot compensate. Burroughs (1974) indicates that the divergence of heat flux is closely related to the divergence of mass. A rapid export of heat away from the upper environment of a tropical system would, by destabilizing the tropical troposphere, increase upward motion and convection. This could in turn account for "an inspiraling of air, massive rising in the central core, and development, through subsidence, of a warm eye" (Ramage, 1971), all before low-level convergence could compensate for the effects of the rapid upper level divergence.

Nancy was a 40-knot tropical storm at 23Z on the 19th (Figure 20). It is of interest to note that although surface pressures (986 mb) supported winds of 40 to 45 knots, flight level winds (700 mb) were observed to be 55 to 60 knots in the north and west quadrants. With the larger thermal and pressure gradients characteristic of a winter environment, one could expect storms to attain a higher intensity for any given minimum sea level pressure and exhibit greater asymmetry than in summer. Figure 22 illustrates the 250-mb flow at 00Z on the 20th. The ESSA 9 satellite mosaic (Figure 23) shows Nancy on the afternoon of the 20th, after the rapid upper level divergence and large surface pressure falls. Figures 17 and 23 show considerable consolidation of the cloud mass from the 19th to the 20th.

Nancy continued to develop and attained typhoon intensity on the afternoon of the 22nd some 200 nm east-southeast of Yap (Figure 20). By the 24th Nancy had reached her peak strength at 120 kt which she maintained for nearly 24 hours. In her wake, Nancy left considerable destruction. Damage was estimated at $160,000 on Yap and near one million dollars in the Philippines where nearly 5,000 families were rendered homeless (U.S. FWC/JTWC, 1971).

4. SUMMARY AND CONCLUSIONS

It is postulated that the structure and mechanics of all tropical cyclones are similar, regardless of the season in which they occur. Prior to formation of the tropical vortex which developed into Typhoon Nancy, low-level flow along the equator changed from easterly to westerly. Horizontal shear between these westerlies and the easterly trades created a region of positive vorticity (a trough in the wind field) near 5°N. The normal absence of this westerly regime during winter may well be the single most significant feature contributing to the rareness of off-season tropical cyclones in the western North Pacific.

During February 1970, anomalies in the distribution of sea-surface temperature (SST) in the tropics of the western North Pacific contributed positively to vortex development. SST maxima and their associated weak surface trough (in the pressure field) functioned to anchor the near equatorial trough (NET). The above-normal SST also permitted greater than normal thermal buoyancy which produced deeper and more sustained convection. The infrequency of significant SST (1° to 2°C) maxima north of the equator in winter may, in part, explain the rareness of off-season tropical cyclones.

The deep influxes of middle tropospheric moisture observed at Truk and Ponape also contributed positively to the early stages of Nancy's development. The moisture, by hydrostatically reducing the surface pressure, increased the surface pressure gradient, further intensifying the surface trough. Such hydrostatic contributions could be significant in early vortex development where pressure gradients are small. Furthermore, by reducing the effects of evaporation and entrainment, the high middle tropospheric moisture increased the potential for heat accumulation.

Cross-equatorial interactions at all tropospheric levels were important in the early stages of Nancy's development. At upper levels, interactions between the two hemispheres produced strong divergent flow which induced copious convection over the Carolines. At low-levels, the acceleration of westerlies south of the equator spread the realm of westerly flow north of the equator which, upon converging with easterlies, produced strong positive vorticity. During the tropical depression stage, a middle tropospheric surge from the Southern Hemisphere imposed, above the vortex, cyclonic vorticity between the 700- and 250-mb levels. This created a vertical coupling of the lower and upper levels of the system. In addition, the upper level positive vorticity, by reducing ventilation, allowed for the accumulation of heat.

Analysis of the 250-mb divergence patterns showed that divergence above the system changed from -0.5×10^{-5} sec^{-1} to nearly 2×10^{-5} sec^{-1} over a 12-hour period. Over this same 12-hour period surface pressures fell nearly 15 mb, while near the end of the period wall cloud formation was observed. This suggests that formation of an eye may be contingent upon a rapid increase of upper level divergence above the system.

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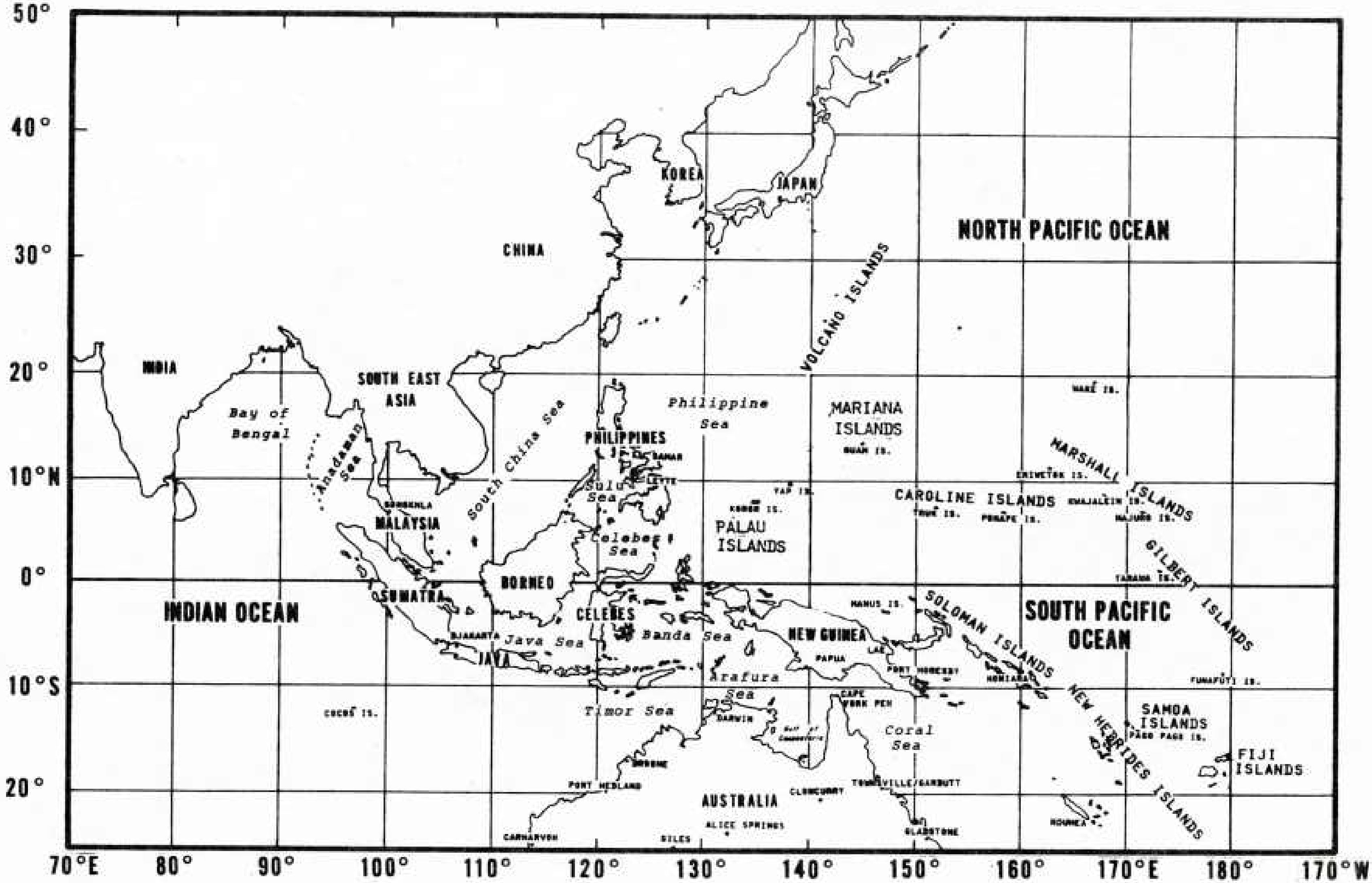

Figure 1. Locator map

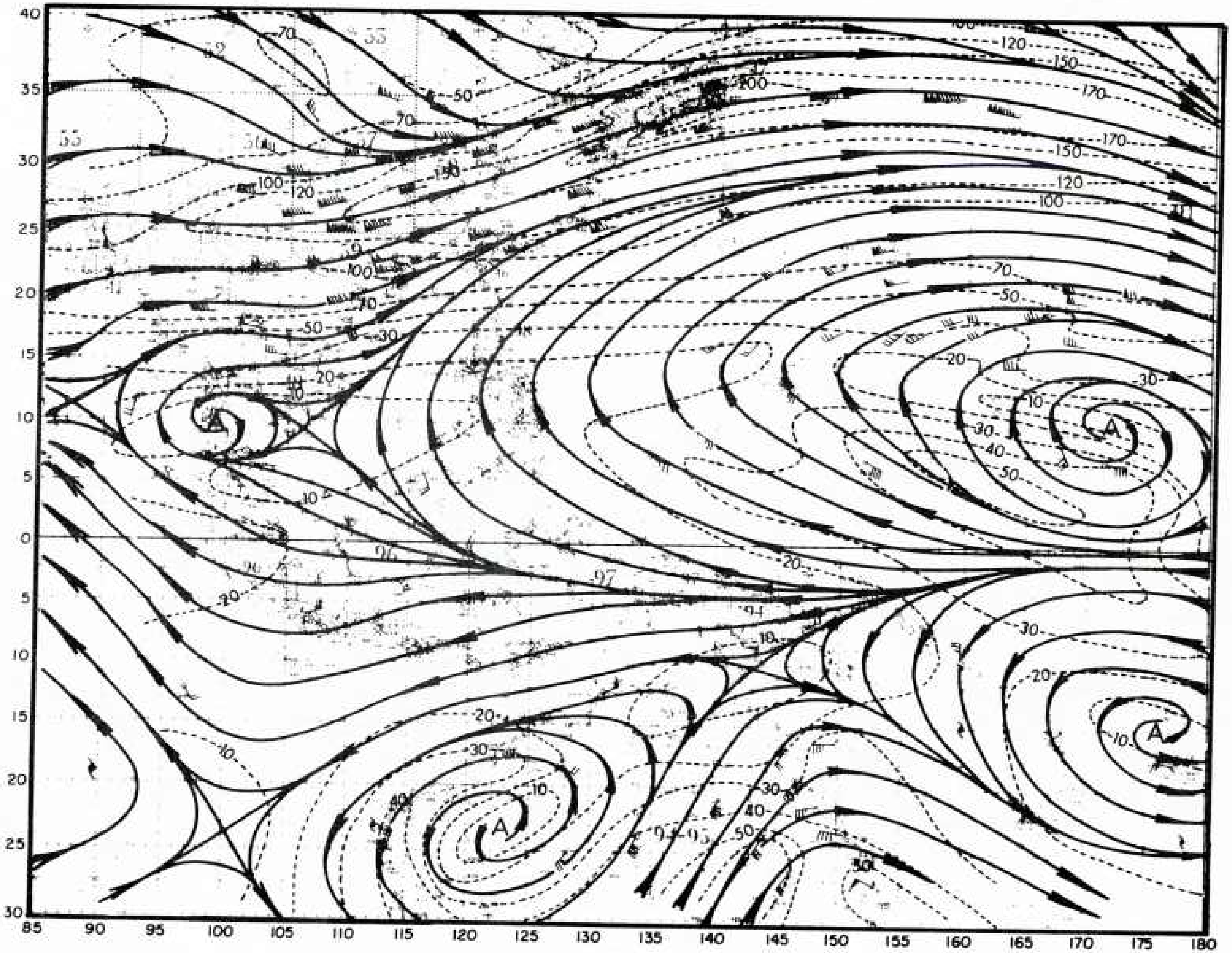

Figure 2. 250 mb streamline and isotach analysis for 00Z 16 February 1970. Streamlines are full and isotachs are dashed (knots).

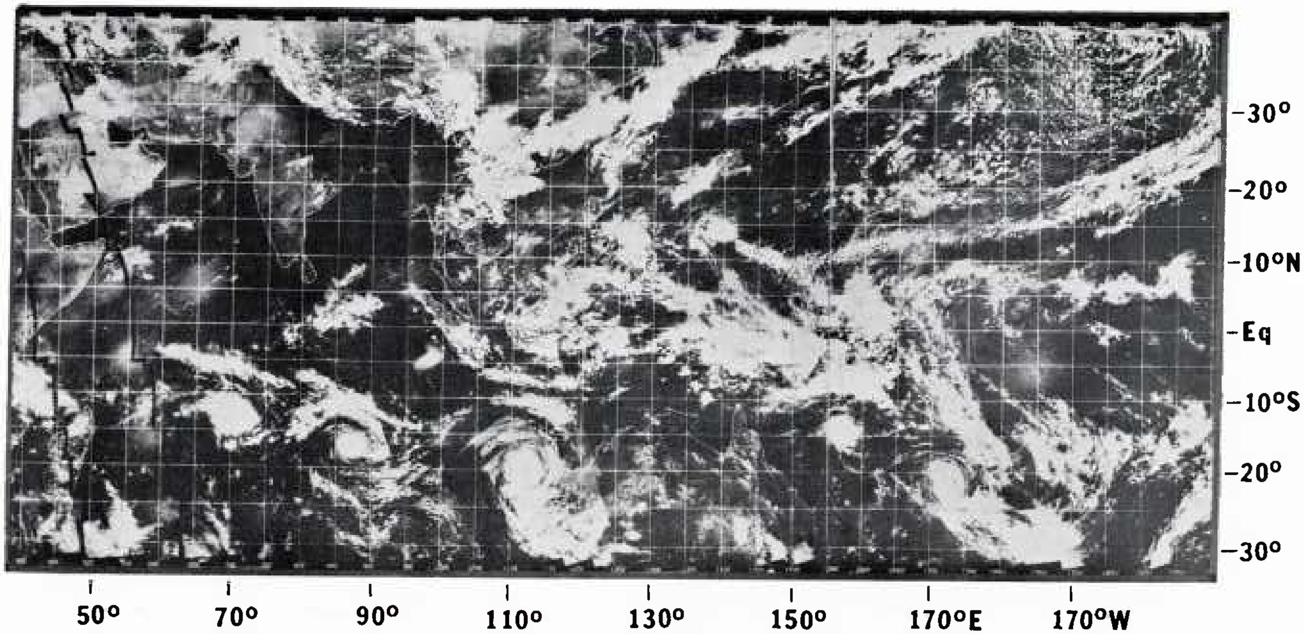

Figure 3. ESSA 9 satellite mosaic photograph for 15 February 1970.

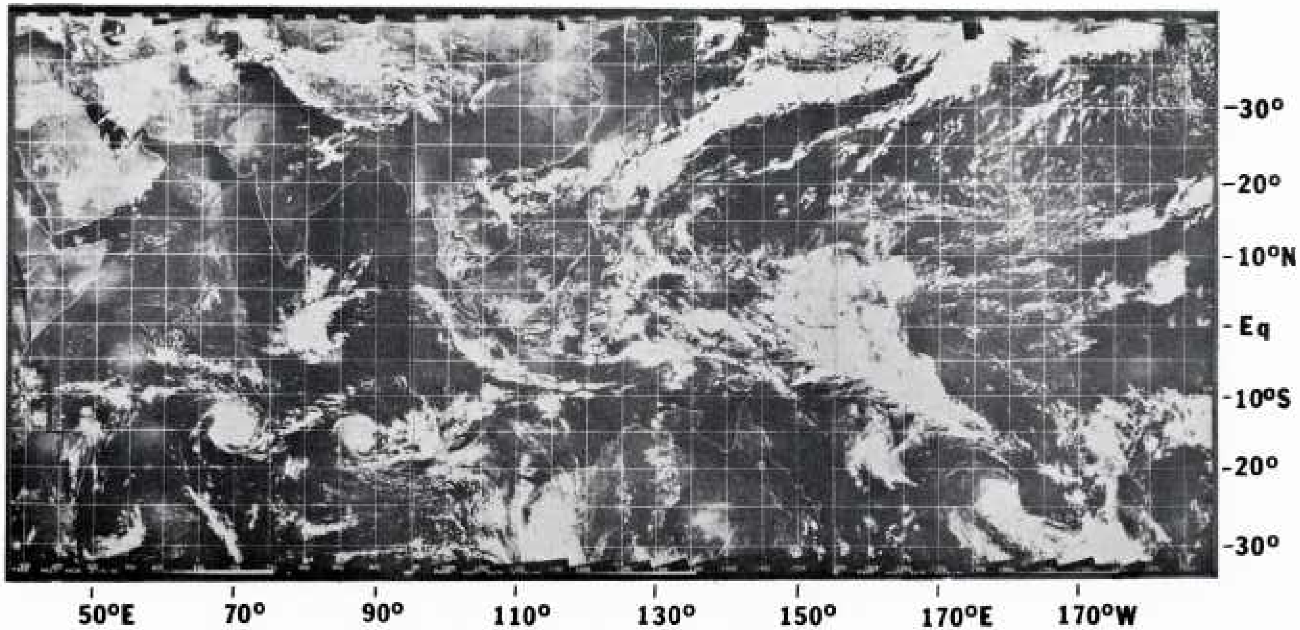

Figure 4. ESSA 9 satellite mosaic photograph for 16 February 1970.

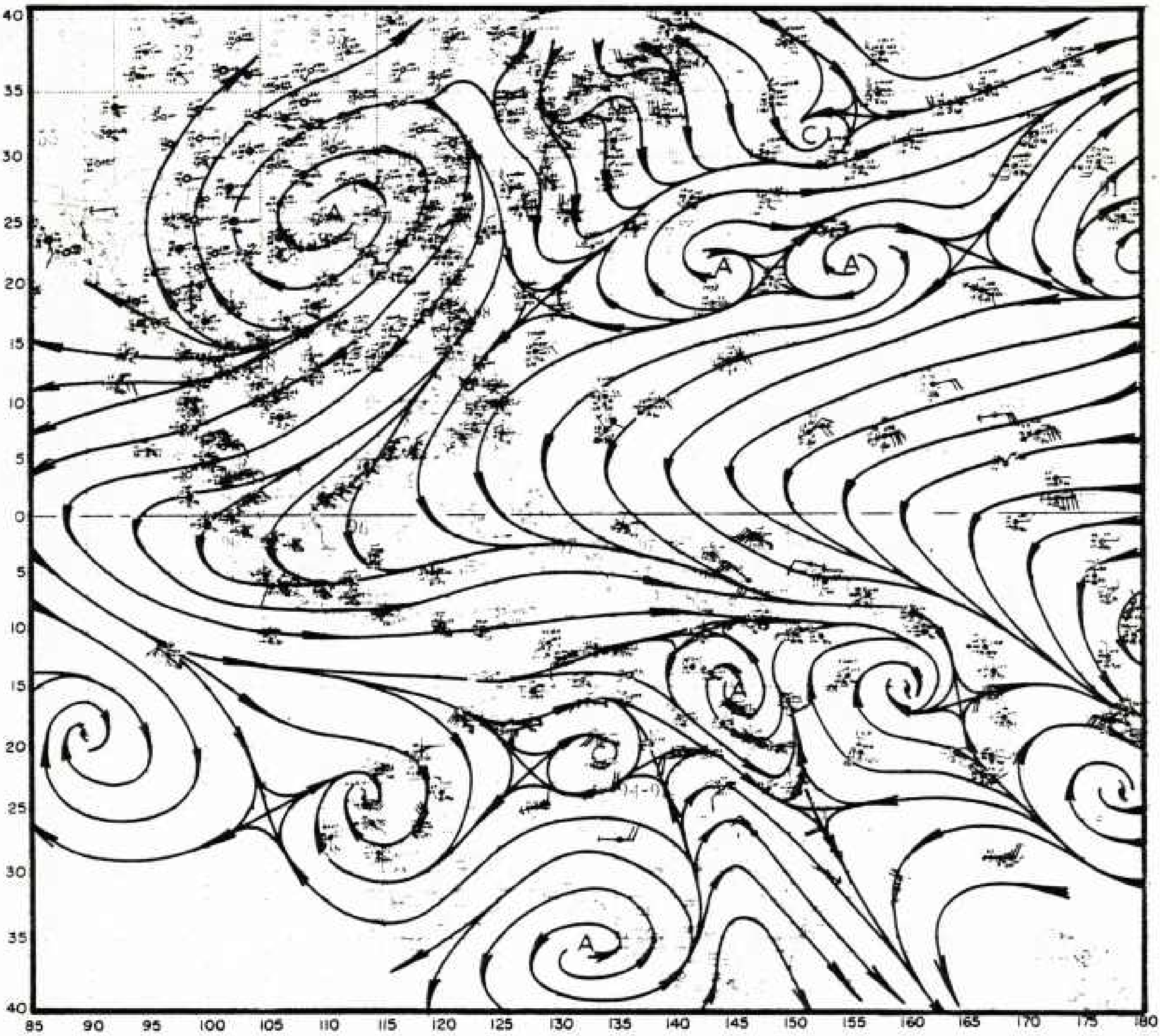

Figure 5. Surface and gradient level streamline analysis for 00Z 16 February 1970. Winds are in knots.

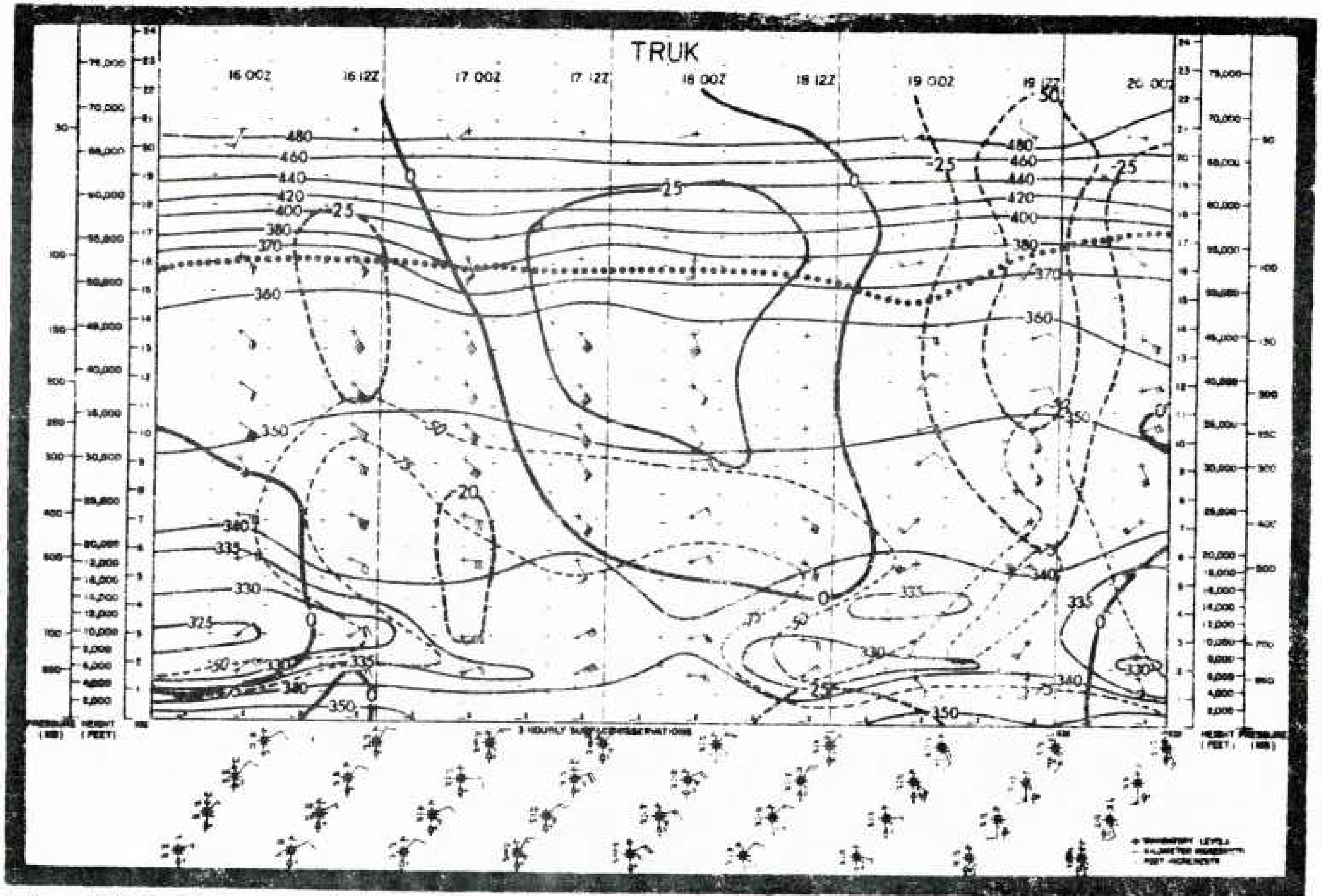

Figure 6. Time cross-section for Truk (07°28'N, 151°51'E) from 16-20 February 1970. Positive geopotential height differences are shown thick and full (m); negative geopotential heights are shown thick and dashed (m); equivalent potential temperature, Θ_e, is shown thin and full (°K); isohumes are shown thin and dashed (%); the tropopause is shown dotted; and wind speeds are indicated by the flags on the wind barbs (knots). Triangular flags are 50kt, full flags are 10kt, half flags are 5kt and no flags are less than 3kts. Three hourly observations begin in the lower left corner with 18Z 15 February 1970.

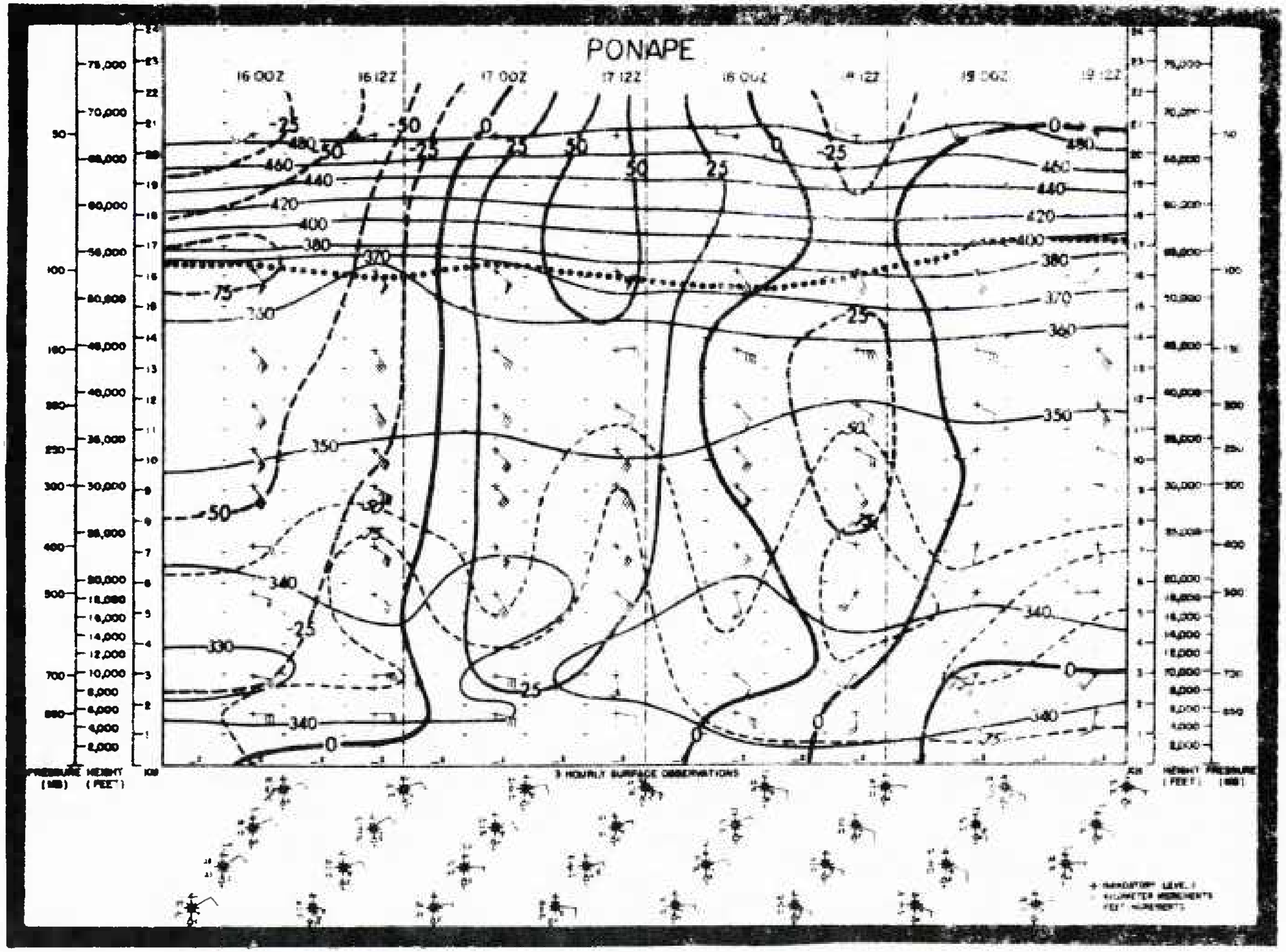

Figure 7. Time-cross section for Ponape (06°58'N, 158°13'E) from 16-19 February 1970. Positive geopotential height differences are shown thick and full (m); negative geopotential height differences are shown thick and dashed (m); equivalent potential temperature, Θ_e, is shown thin and full (°K); isohumes are shown dotted, and wind speeds are indicated by the flags on the wind barbs (kt). Triangular flags are 50kt, full flags are 10kt, and half flags are 5kt. Three hourly observations begin in the lower left corner with 18Z 15 February 1970. (12 hourly fluctuations in the isohumes suggests a poorly ventilated rawinsonde instrument).

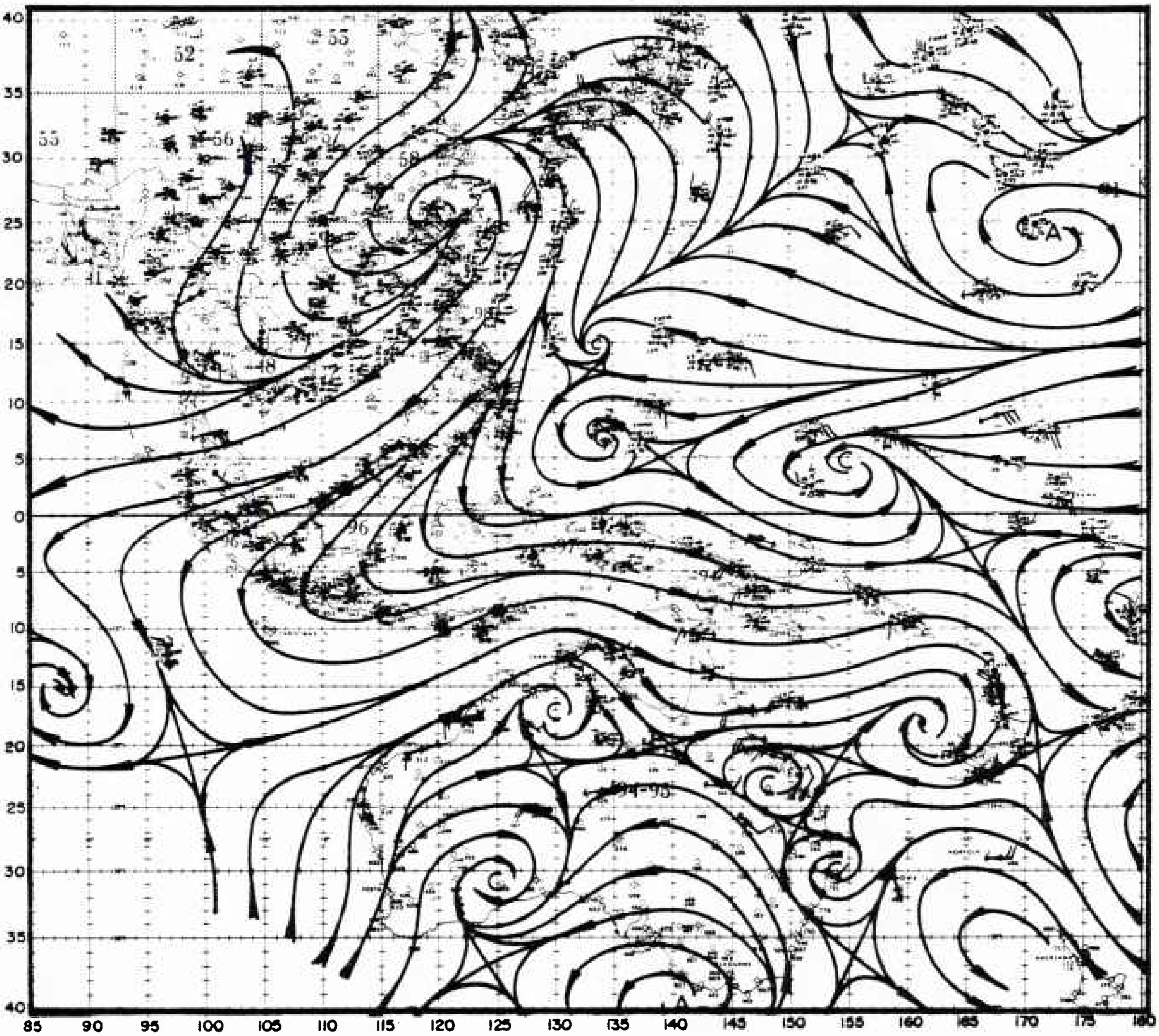

Figure 8. Surface and gradient level streamline analysis for 00Z 17 February 1970. Winds are in knots.

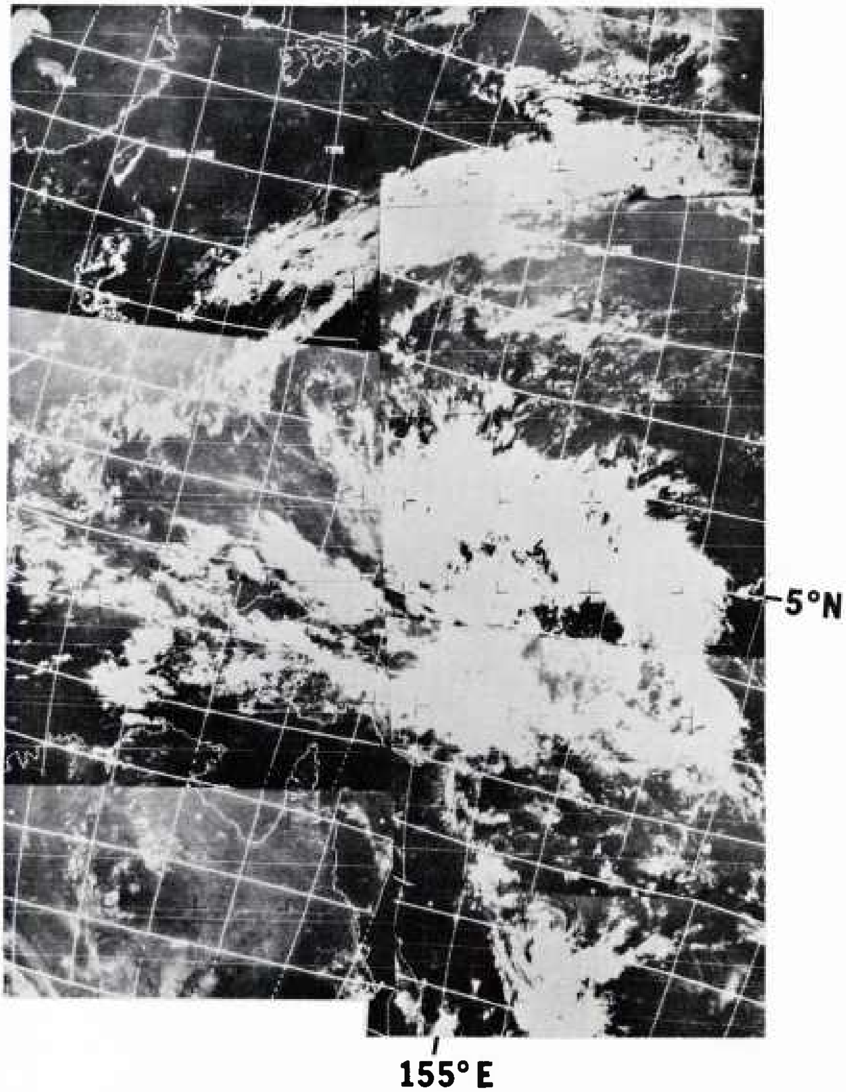

Figure 9. ESSA 9 satellite orbital composite photograph for 17 February 1970.

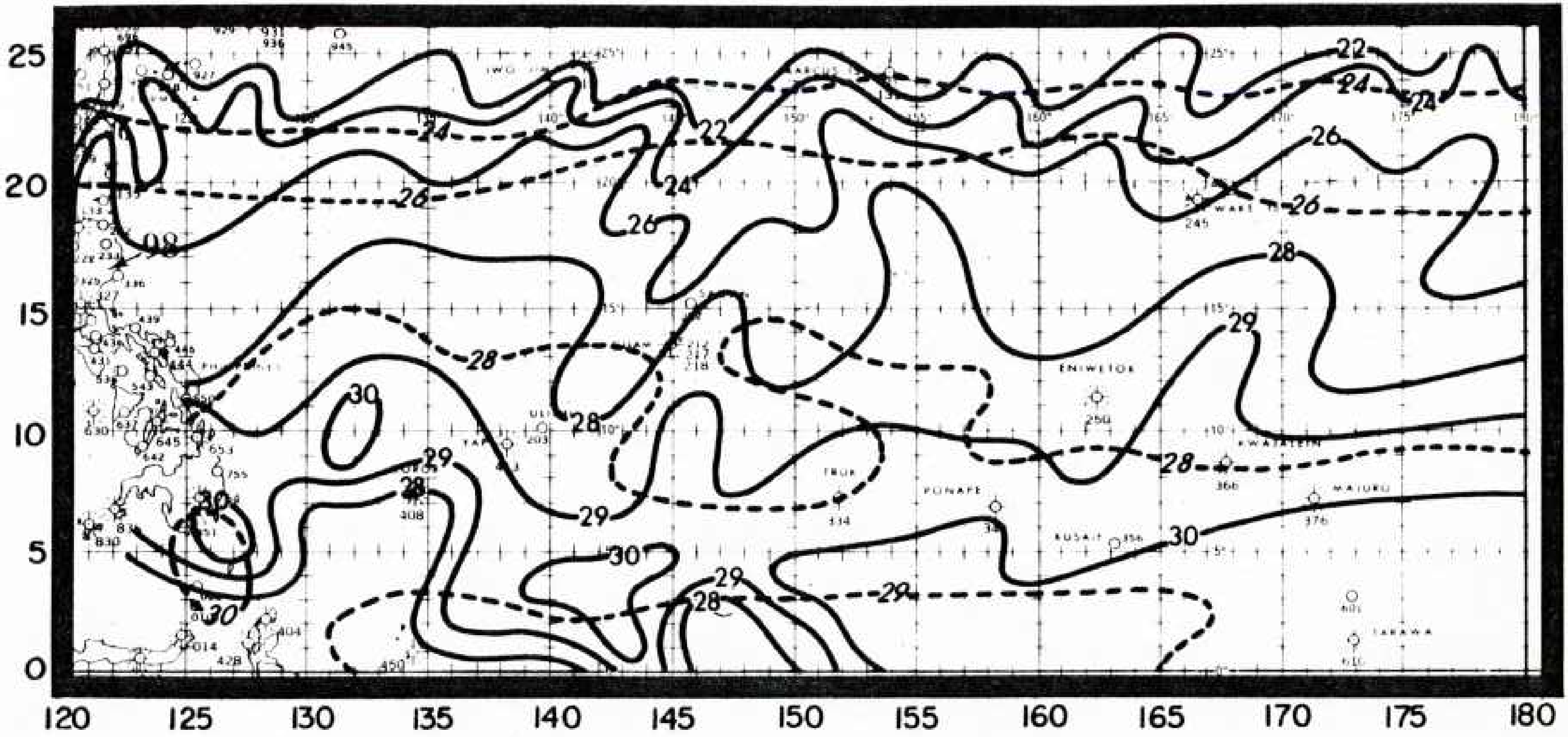

Figure 10. Sea surface temperature analysis for February 1970 (full lines) and the February long term mean sea surface temperature (dashed lines). Temperatures are in degrees Centigrade.

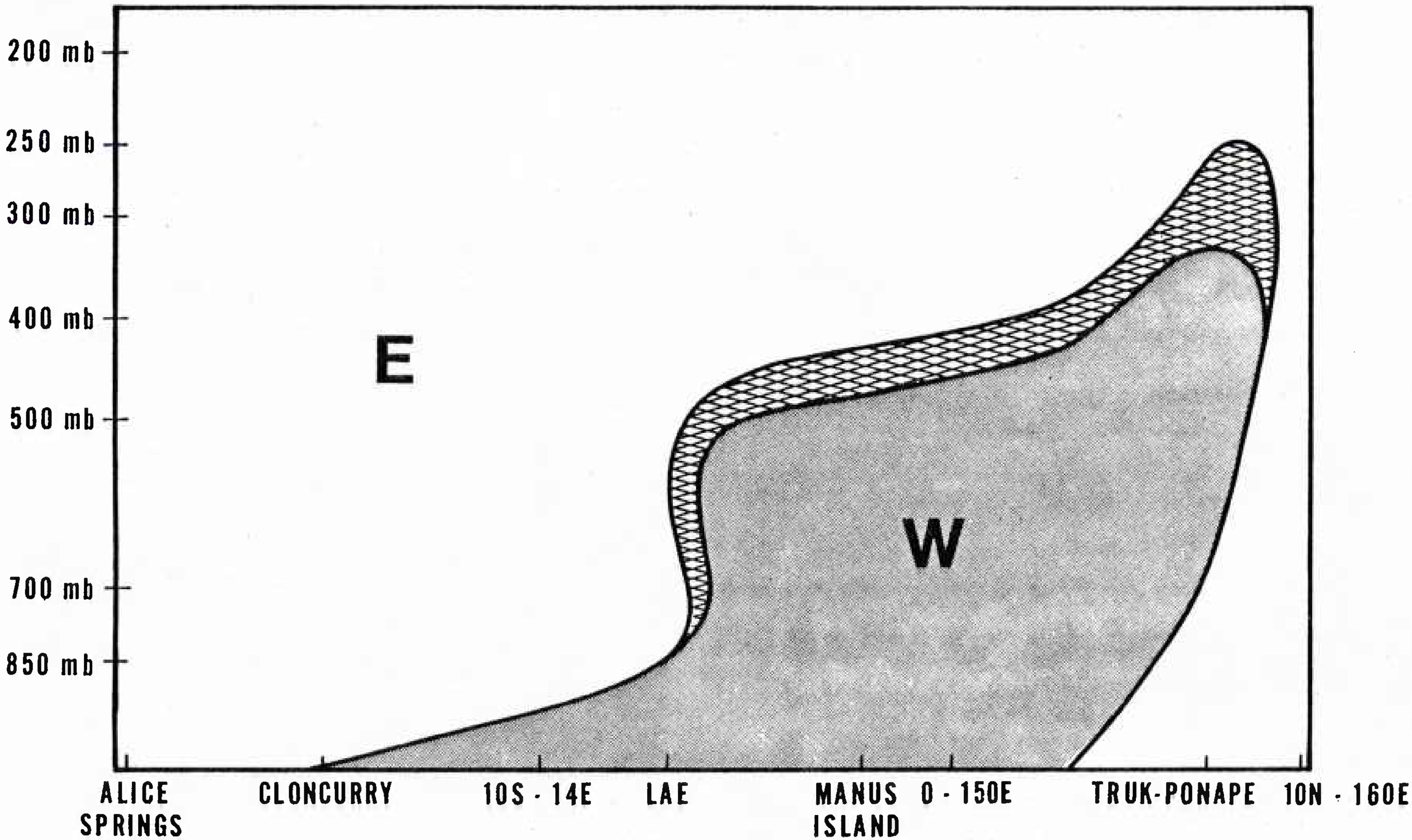

Figure 11. Vertical wind profile from Australia to the Caroline Islands (19 Feb 00Z). White area is easterly, shaded westerly and hatched easterly at Truk and westerly at Ponape.

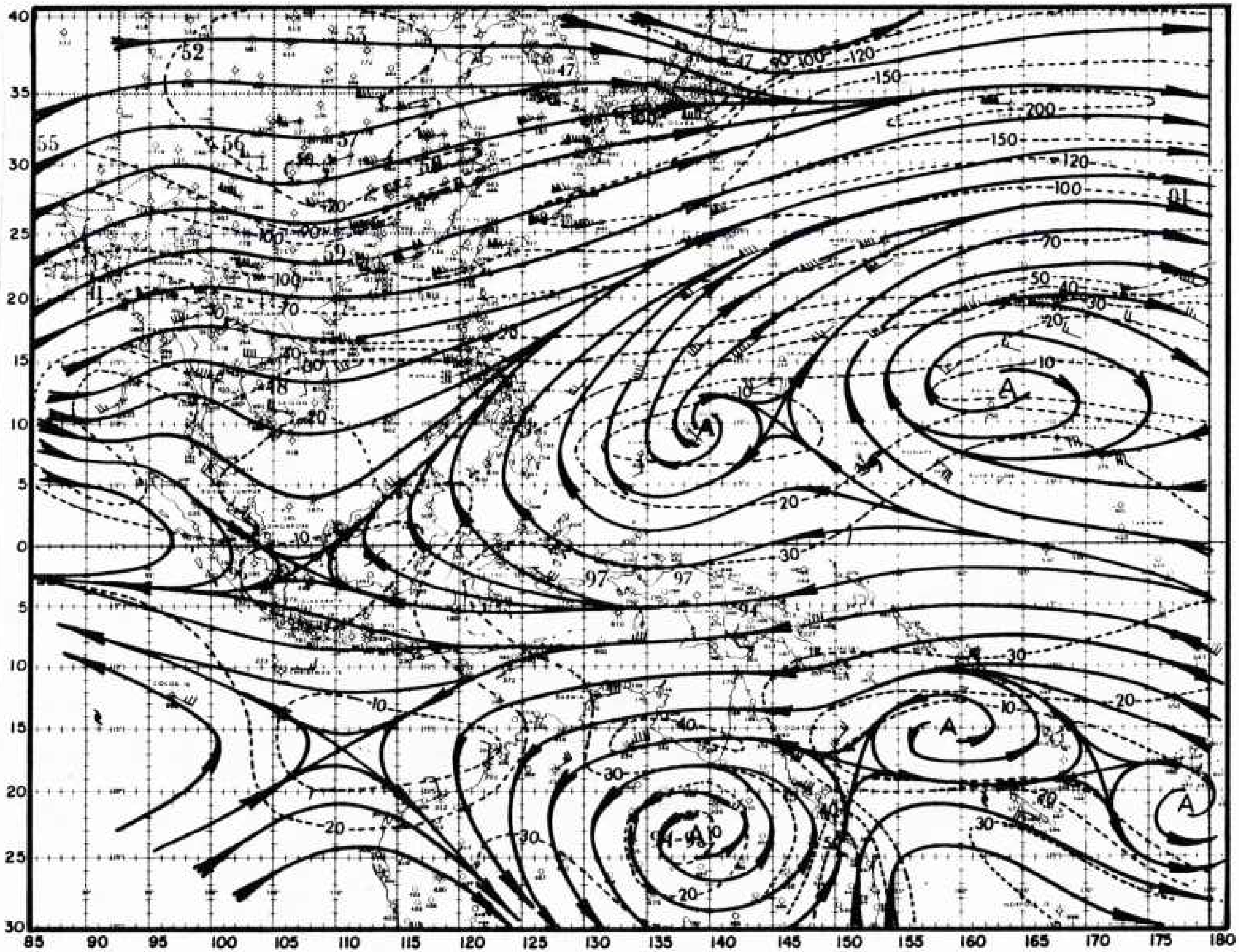

Figure 12. 250 mb streamline and isotach analysis for 00Z 18 February 1970. Streamlines are full, and isotachs are dashed (knots).

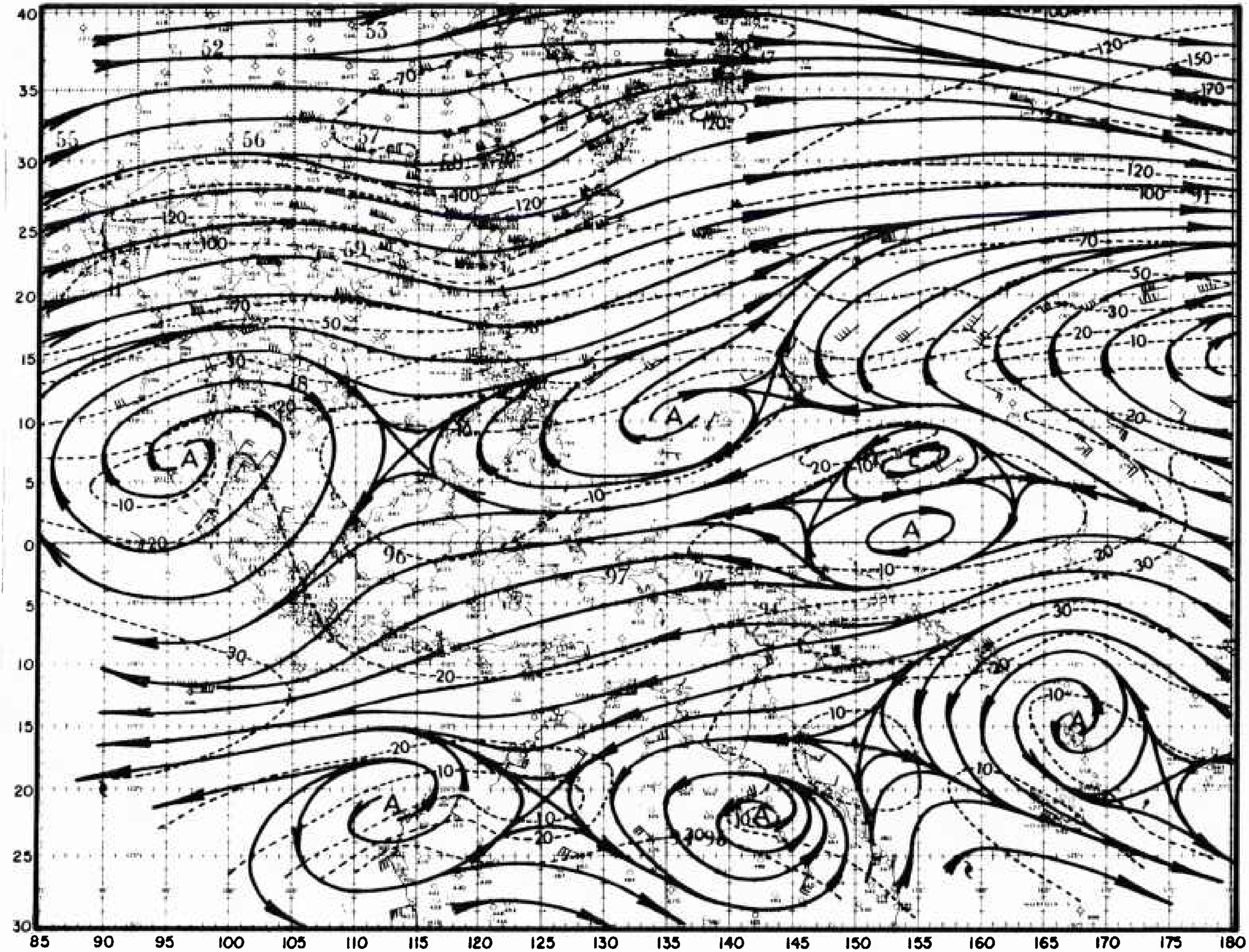

Figure 13. 250 mb streamline and isotach analysis for 00Z 19 February 1970. Streamlines are full, and isotachs are dashed (knots).

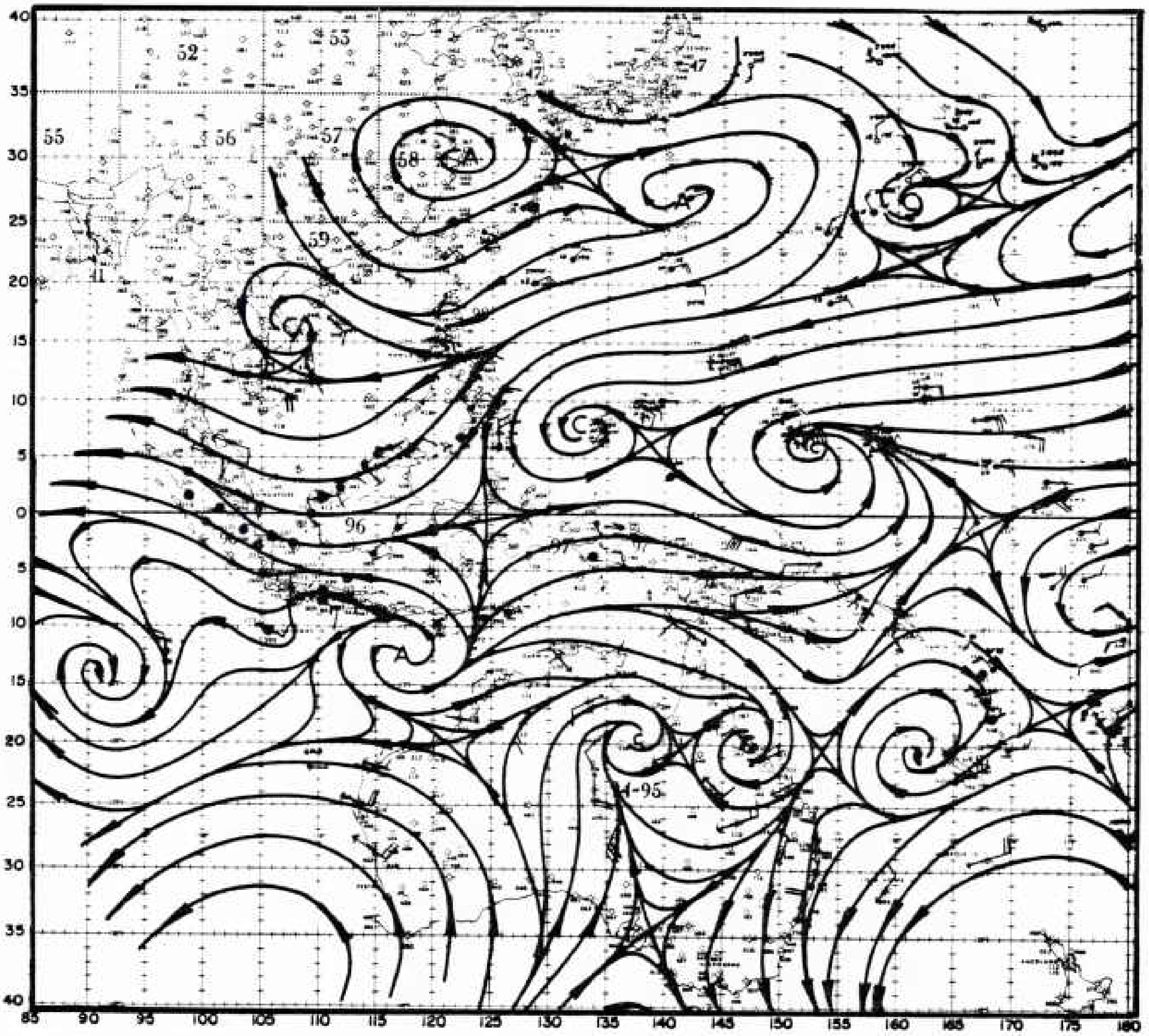

Figure 14. Surface and gradient level streamline analysis for 00Z 18 February 1970. Winds are in knots.

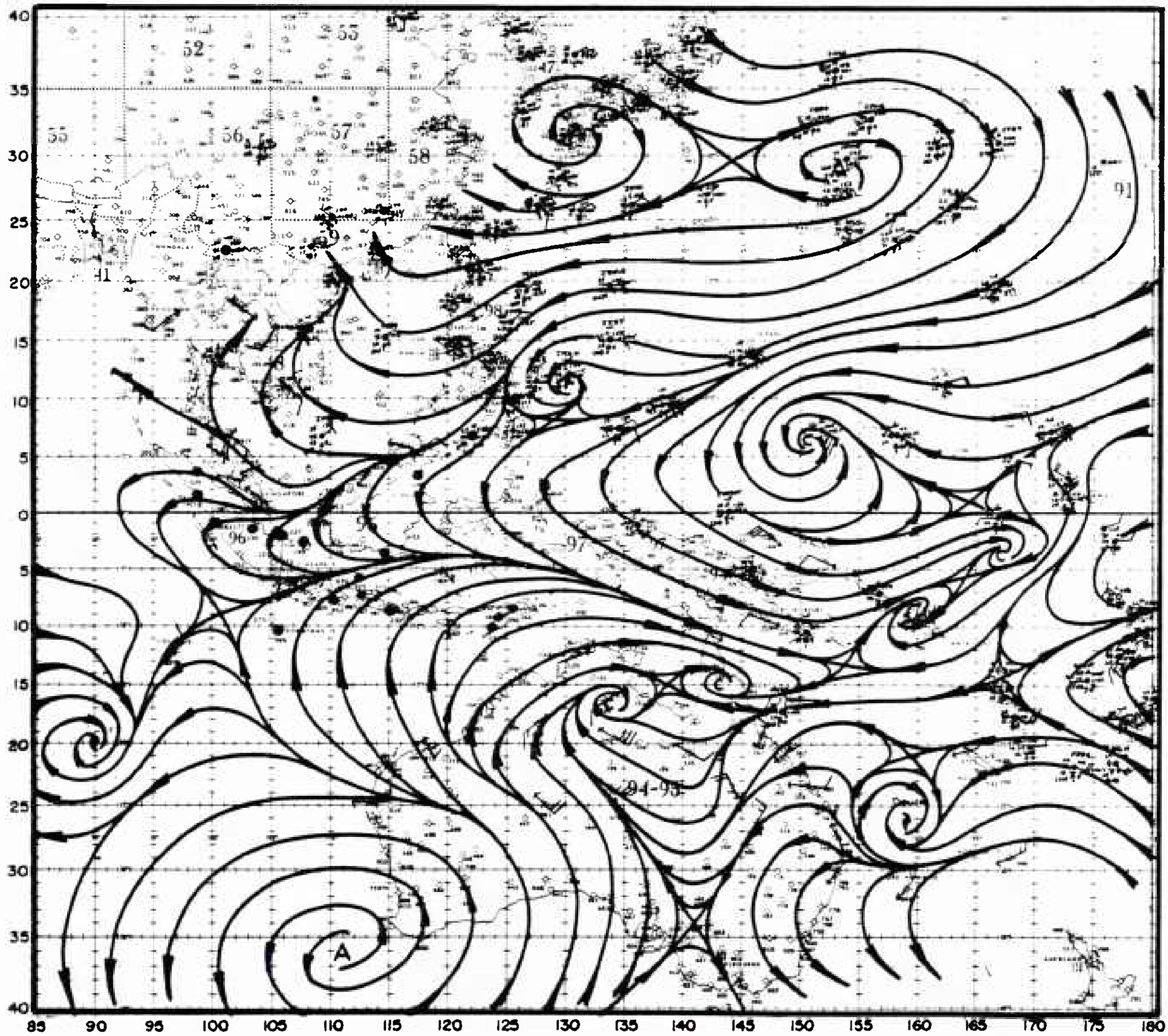

Figure 15. Surface and gradient level streamline analysis for 00Z 19 February 1970. Winds are in knots.

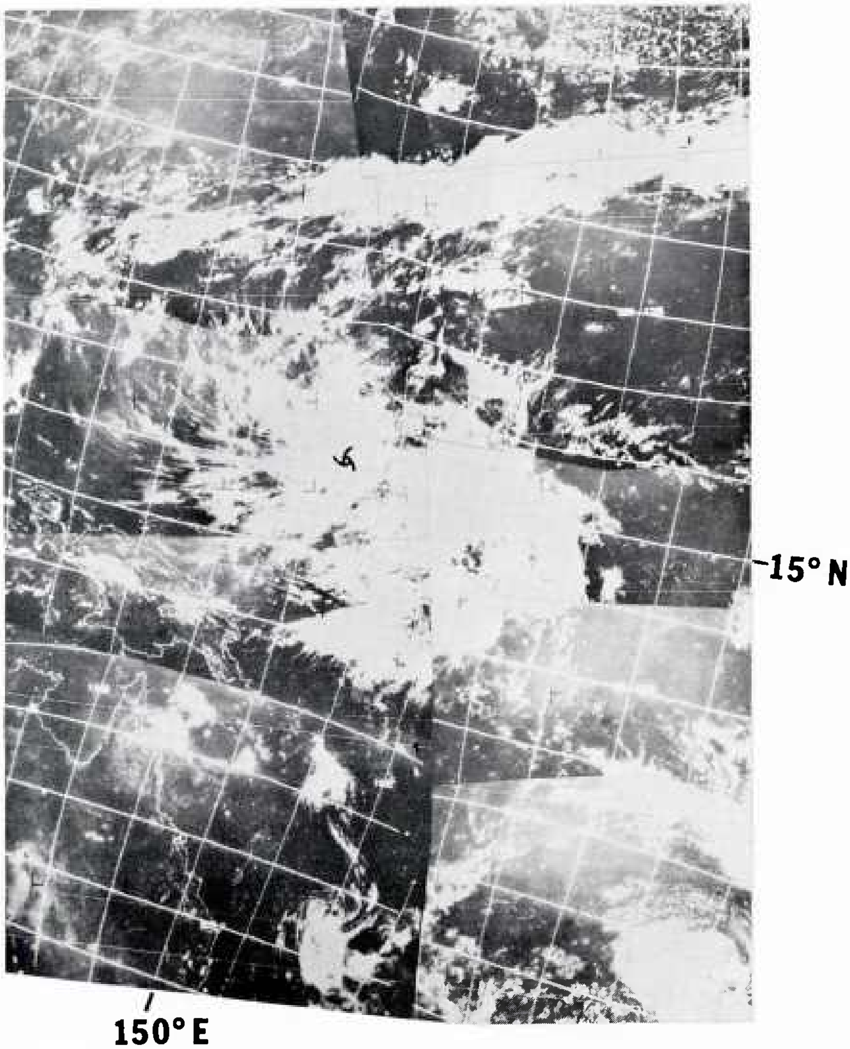

Figure 16. ESSA 9 satellite orbital composite photograph for 18 February 1970.

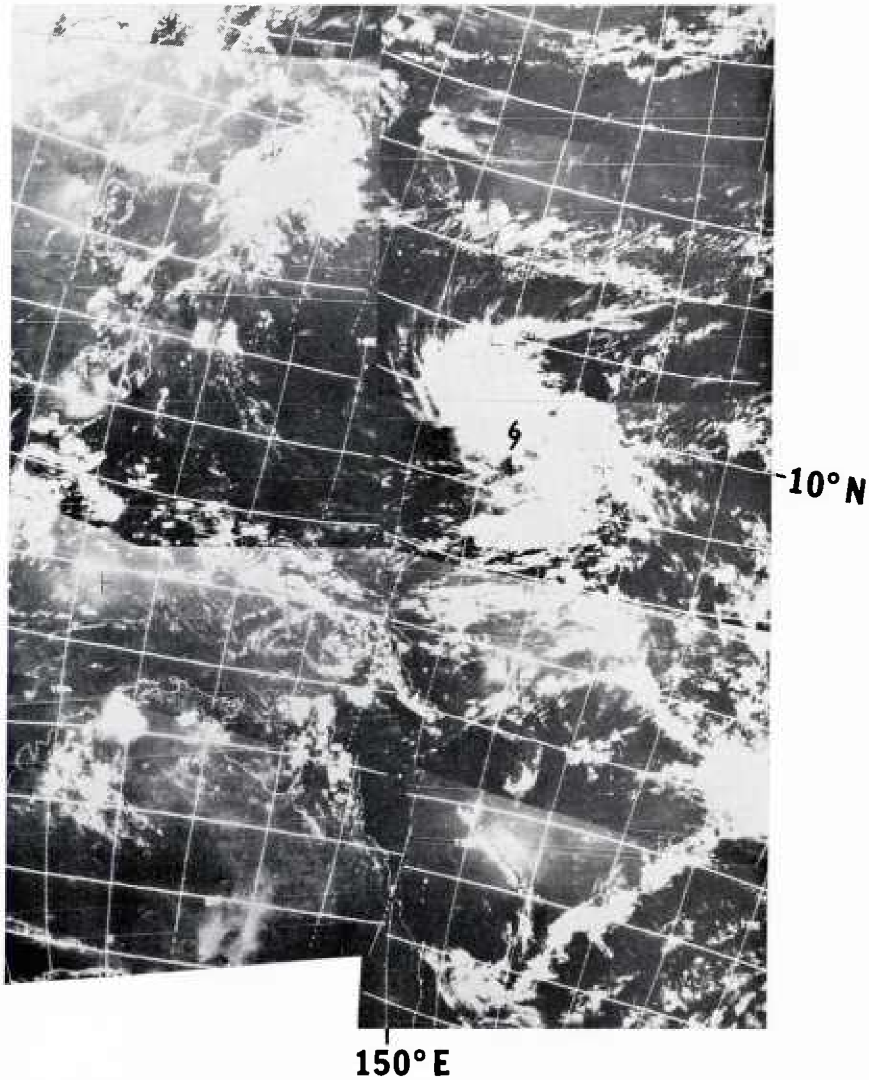

Figure 17. ESSA 9 satellite orbital composite photograph for 19 February 1970.

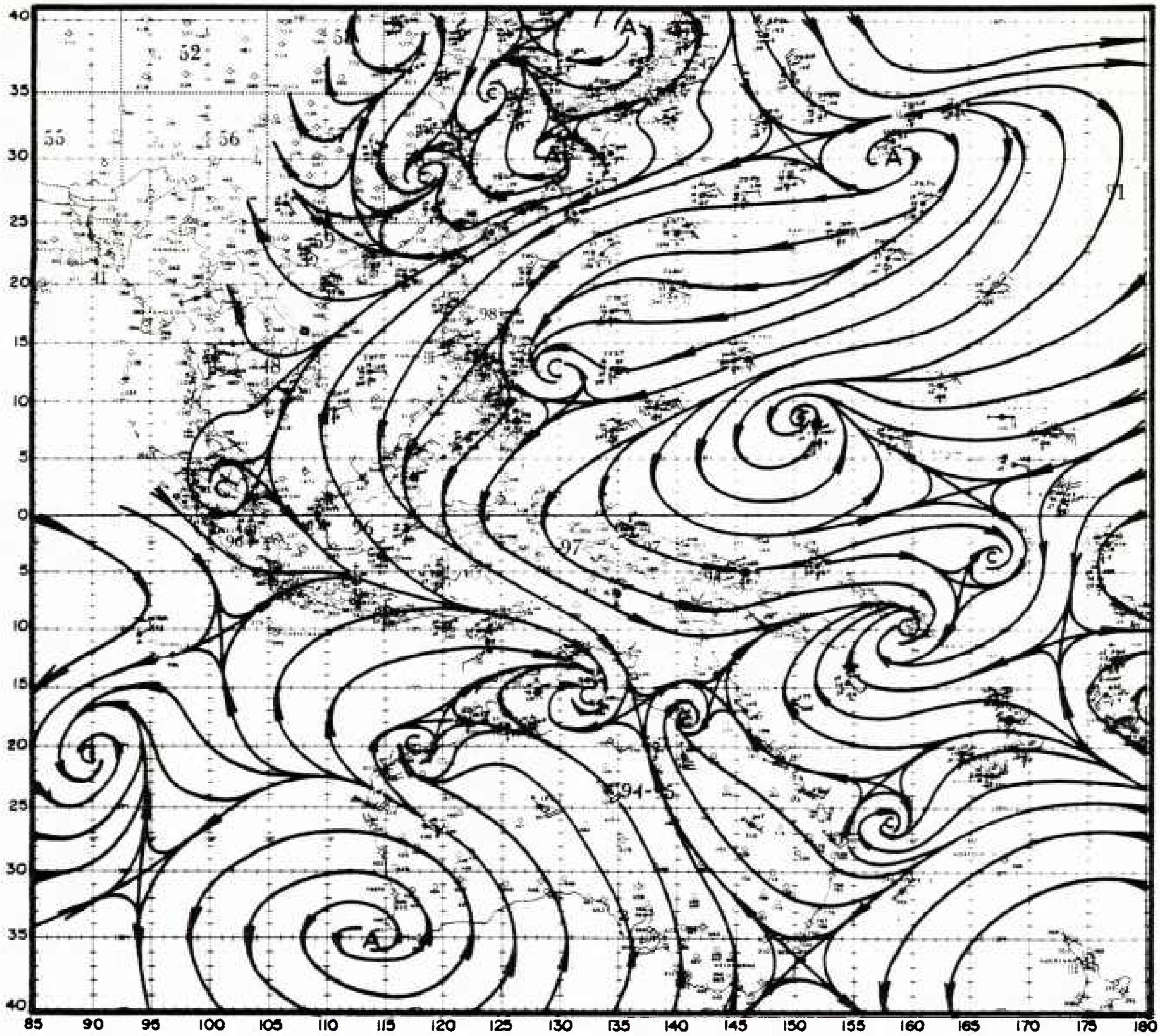

Figure 18. Surface and gradient level streamline analysis for 12Z 19 February 1970. Winds are in knots.

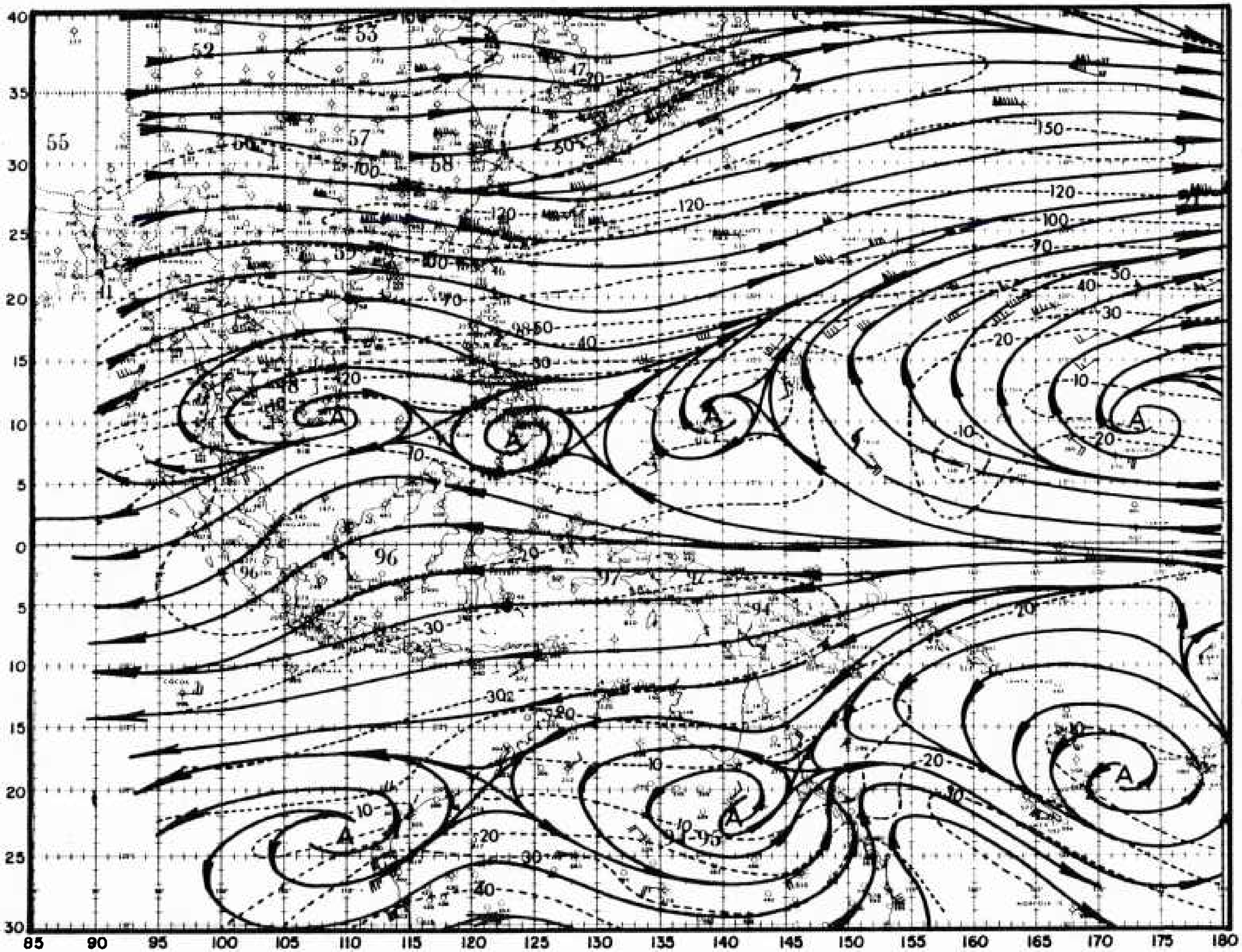

Figure 19. 250 mb streamline and isotach analysis for 12Z 19 February 1970. Streamlines are full, and isotachs are dashed (knots).

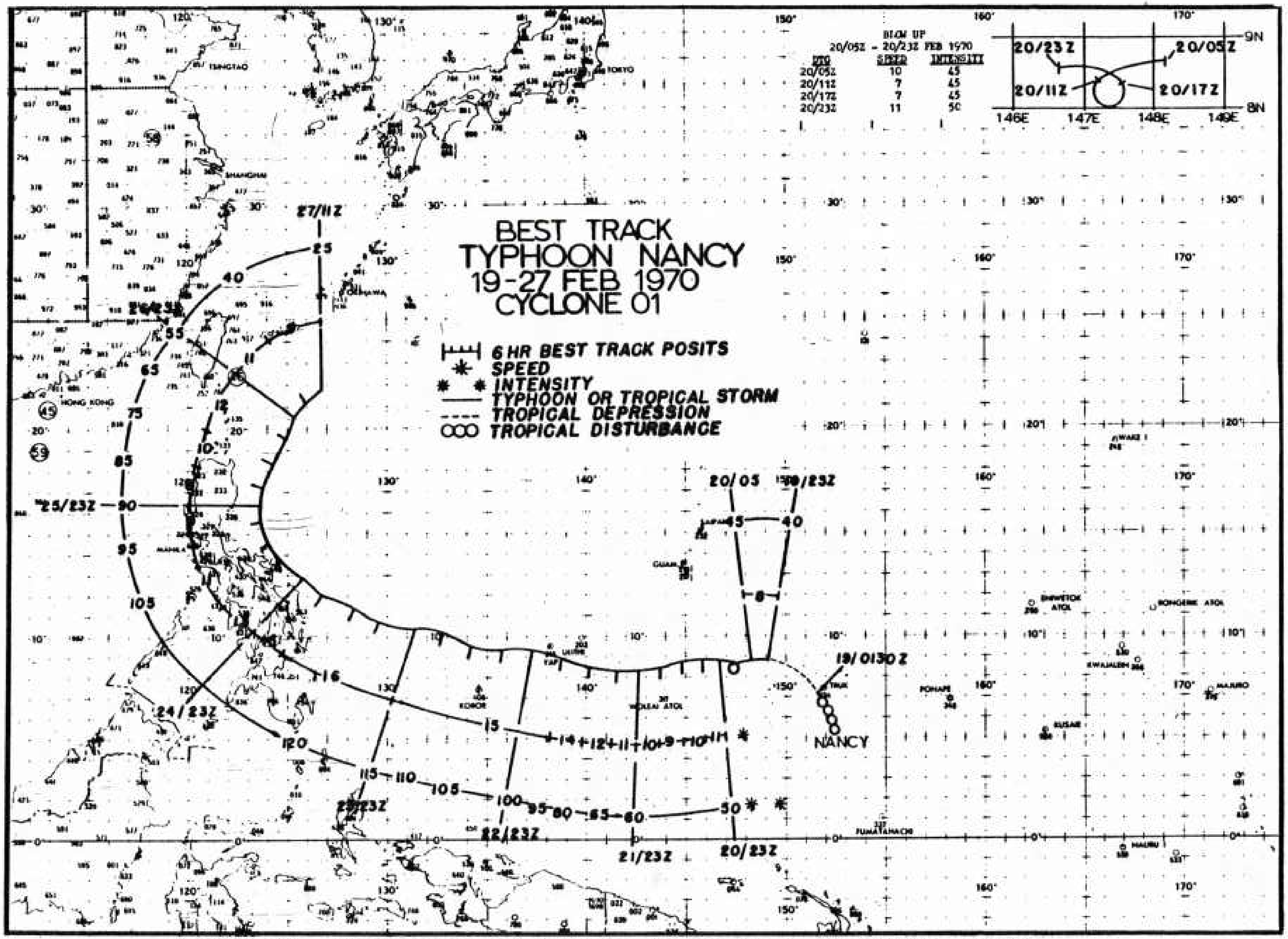

Figure 20. Best track of Typhoon Nancy (U.S. FWC/JTWC, 1971)

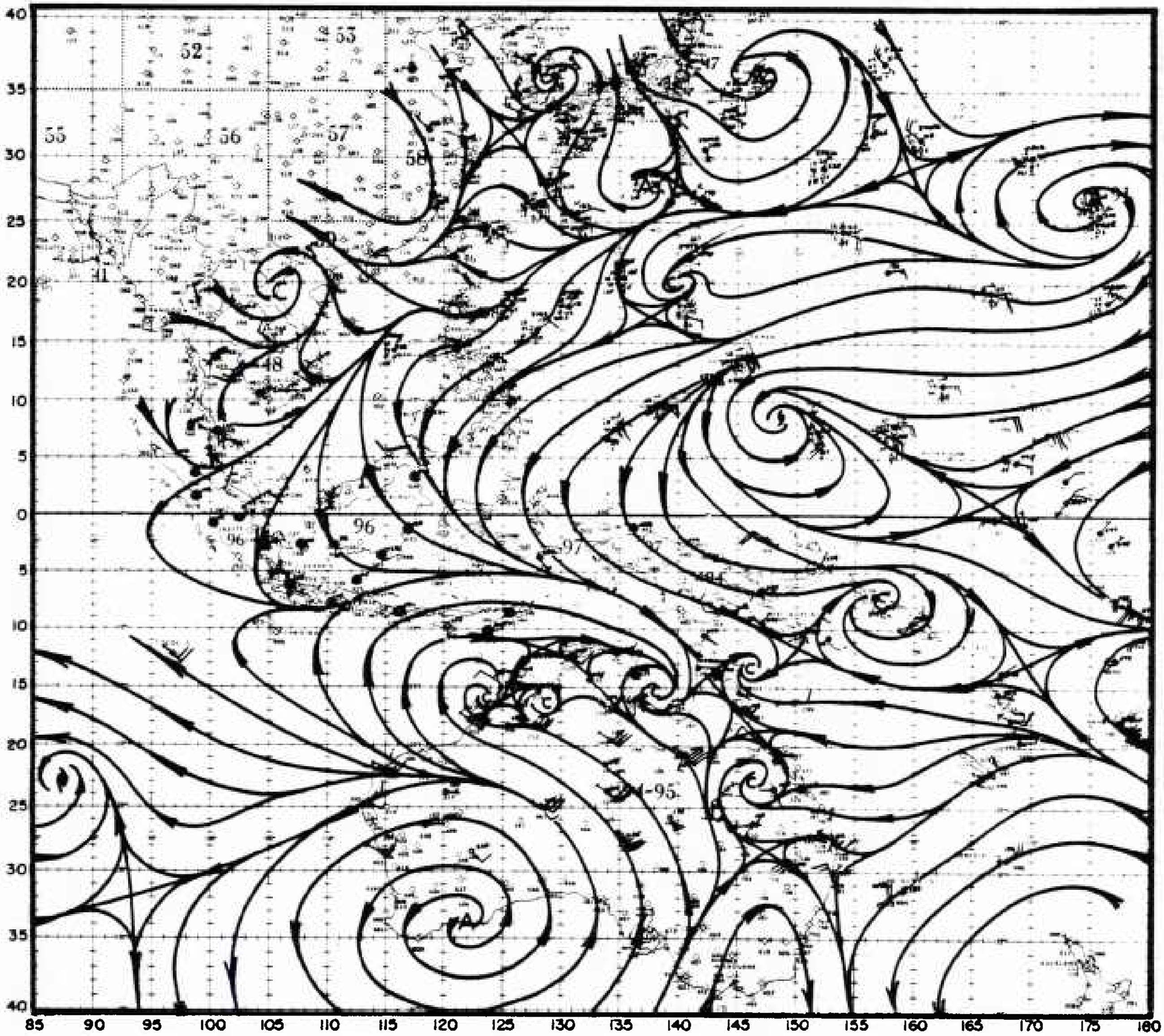

Figure 21. Surface and gradient level streamline analysis for 00Z 20 February 1970. Winds are in knots.

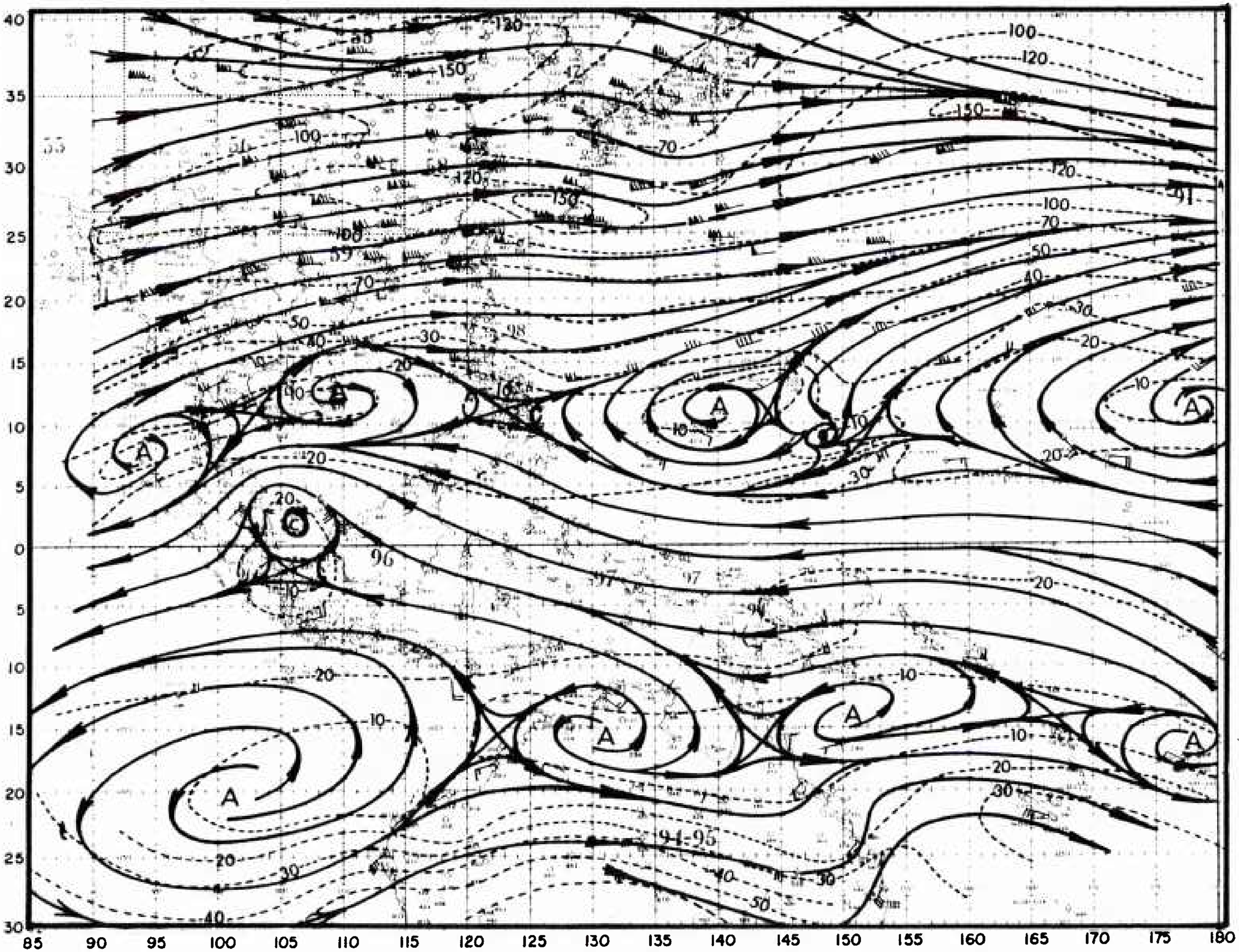

Figure 22. 250 mb streamline and isotach analysis for 00Z 20 February 1970. Streamlines are full, and isotachs are dashed (knots).

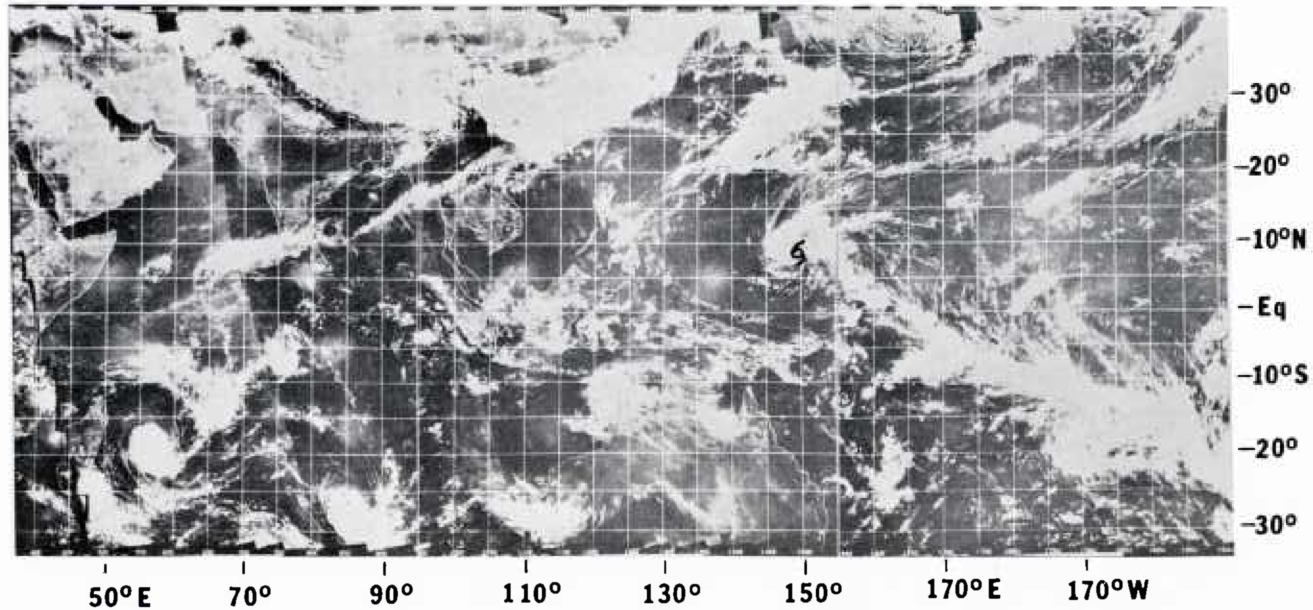

Figure 23. ESSA 9 satellite mosaic photograph for 20 February 1970.